PV Inverter Testing, Modeling, and New Initiatives

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ABSTRACT

Photovoltaic (PV) system reliability has improved significantly over recent years while system costs have declined. Yet reliability still falls short of expectations. Studies indicate a disproportionate number of reliability issues in the PV system are attributed to the power electronics devices of the system [1]. DOE has a two-forked approach to increase the reliability, enhance the performance, and reduce the cost of the power-converting device in a Photovoltaic (PV) system. These two approaches are to continue working with existing and new domestic inverter manufacturers and to leapfrog the existing technology with the DOE high reliability inverter initiative spearheaded by Sandia National Laboratories. Presently the PV industry is in the position to develop an inverter that will utilize innovative technologies, the latest in power electronics devices and associated components, and enhanced quality control and manufacturing processes as the bases for achieving the initiative's objectives. This report will summarize the present issues with utility interconnected PV inverters and the status of the high reliability inverter initiative.

1. Introduction

Reliability in PV systems has experienced significant improvements over the past 10 years, yet the inverter mean time to first failure (MTFF) is about five years [2]. This is an unacceptably short period for the power electronic product to operate since other major PV systems components are designed to operate in excess of 25 years. Achieving high reliability without increasing the cost of the inverter restricts the approaches manufacturers are allowed to pursue. Over design or redundancies in the design can improve the reliability, however, these approaches will lead to higher costs. Another approach, which fulfills both objectives, is a design approach that identifies all requirements, knowledge of component failures, mode of failures, and detailed operating environments. This information is then fed back into redesigns.

Validating the design approach is best accomplished through laboratory evaluations. Recent laboratory evaluations on existing (UIPV) inverters continue to identify performance and functionality issues that contribute to unreliable fielded PV inverters. A contributing factor to the lack of reliability and performance can be attributed to low volume in the production of PV inverters, which results in a lack of qualified component suppliers, inadequate manufacturing quality control procedures, and lack of software version control.

2. Sandia UIPV Inverter Activities

Sandia National Laboratories Distributed Energy Technologies Laboratory (DETL) has performed numerous evaluations of PV inverters ranging in size from $100W_{ac}$ to $100kW_{ac}$. Inverter evaluations involve two types of products. The first type of product is readily available to the public and the second type is a developmental prototype where the manufacturers are seeking assistance.

Historically there has been no single document providing design requirements for UIPV inverters. Standardized test protocols were developed at the DETL in order to bring diverse requirements together. The DETL grid-tied test protocol includes tests for compliance to today's standards. Examples are IEEE Std. 519[3] for harmonic distortion, FCC Part 15 [4] for radio-frequency emissions, and IEEE/ANSI 62.41 [5] for surge voltages in low voltage ac power circuits. The grid-tied test plan was designed to evaluate the performance and utility compatibility of UIPV inverters. An inverter undergoing grid-tied evaluations will be operated over a range of electrical and environmental conditions while recording the inverter's response.

3. Benchmarking of UIPV Inverters

These tests are performed periodically to establish the capability of inverters that are presently available to the public. The evaluations are performed to determine if the inverter adheres to manufacturer specifications. PV inverter evaluations continue to identify performance, interconnection, and reliability issues. Validating the performance and adherence to the interconnection requirements provides manufacturers valuable information on their products. A 2-4-page report is then provided to the manufacturer and with their permission the results of these tests are made available at www.sandia.gov/pv/.

4. Developmental Evaluations of UIPV Inverters

As resources permit, the DETL assists inverter manufacturers to evaluate innovations or new product developments in a controlled, proprietary-protected environment. Failures are expected to occur and do occur during development testing. Consequently, the results of these tests are rarely made available to anyone other than the manufacturers.

Access to the test equipment and personnel at DETL has been extremely valuable to manufacturers, many of whom are not able to invest the resources required to develop an extensive in-house test capability. Most of the evaluations have been conducted at the request of inverter manufacturers seeking information on products, which are still in beta phase of development and are not yet ready for production. Specialized utility-interconnection tests provide valuable information to the manufacturer by identifying interconnection issues or performance issues before the product is fielded. Gaps in product capabilities have been identified through DETL testing and remedied by manufacturers. These testing activities have improved product capabilities and reliability.

5. Utility Compatibility Requirements

Evaluating the responsiveness of UIPV inverters to conditions on the utility that require actions to be taken by the inverter provides the manufacturer with information on the ability for their product to meet UL 1741 [6] requirements. An example of this is evaluating an inverter's response to a disturbance on the utility, which the line voltage sags below 50% of nominal. Such a variation in utility voltage indicates a fault somewhere on the distribution system, thus requires quick actions to be taken. Figure 1 shows the response of a UIPV inverter to a voltage sag that exceeds 50% of nominal voltage. Under such conditions the inverter must respond in 6 cycles to meet interconnection requirements. The data shows the inverter stopped energizing the utility in 3 cycles and opened a contactor in 3 more cycles, thus fulfilling the requirements.

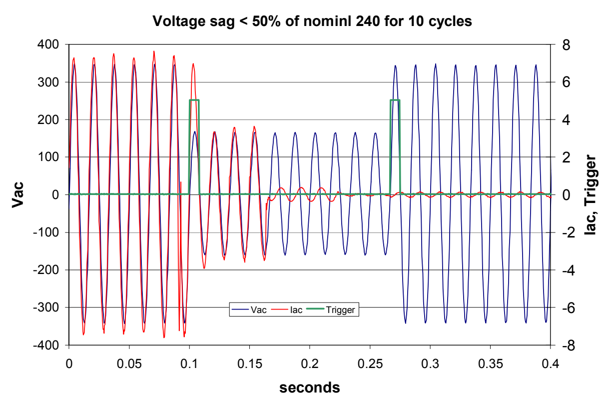

Figure 1. Response to Voltage sags to 50% of nominal

6. High Ambient Temperature Operation

UIPV inverters either rely on active or passive means to remove the heat generated by the power electronic devices. Inverters usually have to operate in rather harsh environmental conditions. These conditions vary greatly from installation to installation. Regardless of the location, each of the inverter manufacturers specifies the operating temperature ranges its product will operate in. Temperature evaluations at DETL have recently detected issues with some UIPV inverters. The inverters are designed to take necessary measures to regulate the temperature of heat sensitive components. This includes scaling back the power available to the utility or momentarily shutting down to maintain a safe operating temperature. Ideally heat mitigation should be accomplished using a passive means since fans have been determined to be a component that will fail prematurely. However, laboratory evaluations have found some inverters that use passive cooling can de-rate the output power to less than 5% of rated power when operating at the maximum power rating.

The test temperature is regulated with Tenney, Model T 14-C chamber, that is capable of lowering or raising ambient temperatures from –54 to 150°C and has air circulation of 3.5 m/s. Figure 2 shows the output power of the inverter while operating at the maximum allowable operating temperature specified by the manufacturer. As the ambient temperature of the temperature chamber is increased to approximately 60ºC the inverter's output power dropped to approximately 110 watts.

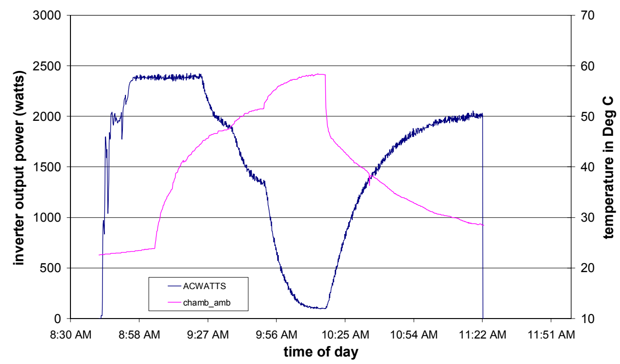

Figure 3. High temperature test of a passively cooled inverter

7. Islanding

Islanding is an issue that will not go away. Most inverter manufactures have had some difficulty in meeting the requirements stated in IEEE Std. 929-2000[7]. Figure 4 shows the results of islanding tests conducted at different power levels on a beta version of a new inverter manufacturer. The RLC (Resistance, Inductance, Capacitance) 60 Hz resonant circuit-islanding test has been difficult for many industry leaders to pass.

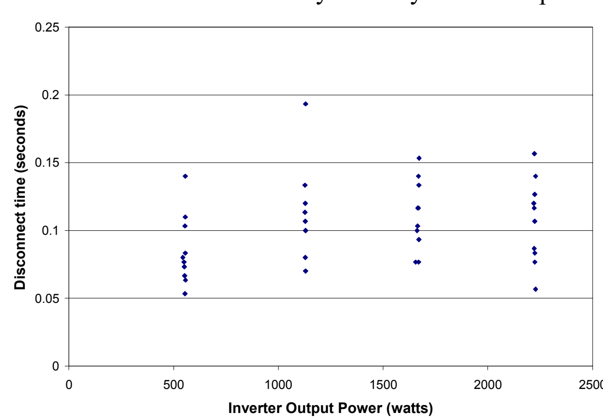

Figure 4. RLC islanding test on new UIPV inverter

Manufacturers are not the only entity seeking information on UIPV inverters. Recently various utilities have requested specialized evaluations be conducted on inverters. These utilities include SMUD, SRP, PNM, APS, PG&E and NYSERDA. The types of tests conducted range from utility compatibility evaluations to multiple inverter islanding tests (not required in UL 1741).

8. Modeling Capability of UIPV Inverter

A detailed model of the Xantrex PV 20208 UIPV inverter was developed and its operation was simulated using PSCAD-EMTDC. PSCAD-EMTC is a variant of the ElectroMagnetic Transients Program (EMTP) and is widely used and accepted by utilities. Xantrex was engaged and is cost-sharing the effort to provide detailed circuit information for the model. Features of the model include voltage and current regulation, the modulation scheme used to generate a sinusoidal output, and ant-islanding schemes used successfully for detection of islanding conditions.

The PV 20208 inverter was installed at DETL and a model of the DETL power grid was developed for use in distribution system simulations. The modeling is currently being validated with a variety of tests being conducted at the DETL. The model has already been used to investigate several utility and standards committee issues including short circuit behavior, islanding detection and maximum power tracking. Figure 5 shows typical waveforms produced by the model.

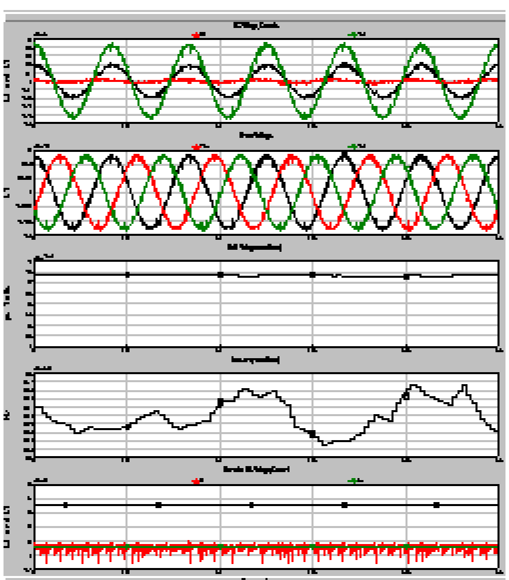

Figure 5. Modeling of UIPV inverters

9. High Reliability Inverter Initiative

The PV inverters have been identified as the component most likely to fail in a PV system. While there have been significant improvements, the effort to rapidly expand the production of UIPV inverters has not improved the reliability of the inverter quick enough to meet milestones set in DOE roadmap projections.

The high reliability inverter initiative emphasizes the need to develop a product that has a MTFF greater than 10 years and is applicable to a variety of distributed energy sources. The initiative aims at achieveing MTFF goals while enhancing performance and adhering to applicable standards. This is to be accomplished while lowing the cost of inverters. Bringing a reliable product to a sustainable market is a major requirement of the statement of work.

It is anticipated that the program will be funded in three phases, Phase I funding was spent in FY2002, with Phase II funding to follow in FY 2003/2004. Prototypes will be built in Phase III in FY2004/2005. The planned structure of these phases is discussed below. Actual program structure will depend on available funding. Contractor cost sharing will be required to emphasize commitment to the program.

Phase I (3 months - up to 3 contractors) was the program formulation phase. During this period of time the requirements were finalized, the product configuration and architecture were determined, and the path to production was determined. The work performed in this phase will be evaluated prior to awarding follow-on contracts.

Phase II (12 months – up to 2 contractors) will require a detailed product design, which includes prototype software modules and some hardware, sufficient to verify designs. Final product design should occur in this phase. The work performed in this phase will be evaluated prior to awarding follow-on contracts.

During Phase III (nine months-up to 2 contractors) final prototypes will be assembled and the facility will be configured for manufacturing. Of special importance during this development phase is testing. Development testing should include functionality, highly accelerated lifetime testing (HALT), environmental testing, and outside product validation testing. The outside product validation will be conducted at the Sandia National Laboratories power electronics laboratory (DETL) as part of the contract oversight function.

10. High Reliability Inverter Initiative Objectives

The objective of the high reliability inverter initiative is to develop an inverter that has a MTFF greater than 10 years, increase the performance of the inverter, while maintaining or reducing the cost of the inverter. Achieving high reliability while reducing costs of the inverter appears to be conflicting goals, yet with proper marketing strategies and understanding the reasons for the lack of reliability in the inverter and implementing solutions, the objectives can be realized.

The inverter size addressed in the high reliability initiative ranges from 1 to 10 kW and is sized to maximize the number of units produced and sold, which will lead to a mature product that fulfills the requirements described in the inverter initiative. The issues that confront the power conversion units are not unique to PV.

The goal of this program is to significantly improve the reliability of the power electronics used in Distributed Energy Resources while containing cost and maintaining performance. This will result in a 'mature product' series of DER inverters with output of from 2 to 500 KVA that have

- High reliability (>10 year mean time to first failure (MTFF)),
- Cost less than or equal to that of current systems
- A market,
- Improved performance, and
- Compliance with all applicable standards for interconnection, performance and safety.

Other distributed energy resources (DER) such as fuel cells, microturbines, and wind all utilize inverters as their utility interface. Fuel cell and micro turbines are just emerging as new technologies, thus interface problems with the inverters are unknown. Ultimately the goal of this program is to significantly improve the reliability of the power electronics used in other distributed energy resources (DER) a long with PV inverters.

11. Identifying cause of premature failures

Today's market uncertainties and diversity have been identified as significant contributors to the lack of reliability in PV inverters. The low volume in sales impedes manufacturers from establishing the necessary network of qualified suppliers. The low volume also impedes the manufacturers from implementing quality control manufacturing processes and from pursuing ISO 9000 certification. Until recently the market for PV inverters has been approximately 1000 units per year. Recent events like the roaming blackouts in California, state-sponsored buy-down incentives, and the diversification in state energy portfolios have cause a significant increase in sales of PV inverters in 1-10kW range.

12. The High Reliability Inverter Requirement

The inverter initiative will require the contract awardees to develop a design of the desired product that meets the listed requirements. The design shall address how the following program goals are met:

- double the current MTFF to >10 years,
- achieve sales volumes of 10,000/year by 2006.

The configuration of the inverter (for example the decision to have storage) is not dictated by this contract. Thus the contractor has the flexibility to propose a design configuration that fits most closely within his own business structure and meets the two program goals above. Requirements for high reliability inverter (with optional storage capability) are:

1. Ten year MTFF (meant time to first failure)
2. Efficiency > 94%
3. UL 1741 certification
4. Meets FCC Part 15, Class B
5. Adequate dc and ac disconnects that meet NEC
6. Heavy duty power connections
7. DC and ac over current protection (over load of 50% for 30 sec)
8. Nonvolatile memory
9. Surge protected per IEEE C62.41
10. Cost of < \$.90/watt (at quantities of 10,000/year)
11. TDD (total demand distortion) < 5% (IEEE 519-1992)

The contractor shall provide an inverter design and shall conduct simulations to verify that the design provides 10-year mean time to first failure (MTFF). The contractor shall demonstrate that inverter cost and performance goals (described above) will be met. The following items shall be addressed in the design and documented in the final report.

1. Switching technology and switching device
2. Intelligent design (ASICs, DSP, etc).
3. Packaging technology that increases reliability and/or reduces cost (laminated power buses, magnetics, bonding techniques, modular design, etc.).
4. Cooling technology and expected operating temperature. Operating temperature margin with respect to safe operating area (SOA) of semiconductors.
5. Manufacturing technology including means for component interconnection.
6. Compliance with regulations (IEEE-929, 519, etc.)
7. Mitigation of lightening induced surges.

13.Conclusion

Laboratory evaluations at the DETL continue to assist manufactures, utilities, and the government. The High Reliability Inverter Initiative puts the PV industry is in a position to develop inverters that have a MTFF in excess of 10 years, meet all the existing interconnection requirements and cost less.

References:

[1] Rick West and Konrad Mauch, Xantrex Power Engineering, Burnaby, BC Canada, Yu Chin Qin, Millenium Technologies, Troy, Michigan, Ned Mohan, U of Minnesota, Minneapolis, MN, Russell Bonn, Sandia National Laboratories, Albuquerque, NM, *"Status and Needs of Power Electronics for Photovoltaic Inverters; Summary Document"*, SAND2002-1085.

[2] R.Pitt "Improving Inverter Quality," *Proceedings, NCPV Program Review Meeting,* April 16-19, Denver, CO, pp.10-20.

[3] IEEE 519-1992. Guide for Harmonic Control & Reactive Compensation of Static Power Converters.

[4] FCC Part 15, Rules land Regulations, Radio Frequency Devices, July 1981.

[5] IEEE C62.41-91, "IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits"

[6] UL 1741, "Static Inverters and Charge Controllers for use in Photovoltaic Power Systems," 1st Edition May 7, 1999.

[7] IEEE 929 Std 929-2000, *IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems,* Institute of Electrical and Electronics Engineers, Inc., New York, NY.

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